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COMPOSITE STRUCTURES TYPE OF CROSS LAMINATED TIMBER AND CONCRETE

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ABSTRACT

The paper presents the presentation of innovative structural elements made of composite materials based on cross-laminated timber (CLT) and concrete. In modern construction more attention is paid to the research and use of ecological, sustainable and renewable materials, all with the aim of reducing and reducing environmental pollution.

In addition to the ecological aspect and the reduction of harmful gas emissions during the production and applying of such materials and constructions, significant progress in improving the mechanical and other characteristics of timber-based materials, i.e. "engineered timber", is evident. Constructions made of cross-laminated timber and concrete, thanks to their physical and mechanical characteristics, can be used for structures of various types of residential buildings, high-rise building structure for the construction of multi-storey residential and commercial buildings and bridge structures of middle spans. The idea of strengthening timber, as a natural material with exceptional characteristics, is not new and throughout history it has developed in parallel with the development of the construction industry and knowledge about the material itself. The concept of using modified timber and combining different types of building materials has developed in the late 20th and early 21st centuries, considering the modern challenges that arise when designing new and reconstructing existing buildings. By coupling timber and concrete and forming unique composite structural elements, the disadvantages of one material are eliminated by the good properties of the other material, and in this way, the relatively low density of a timber and compressive strength of concrete are used very effectively. By coupling cross laminated timber and concrete, with special connecting systems, a composite-hybrid material of high quality is obtained in terms of load-bearing capacity, serviceability and durability. Connecting systems can be of different shapes, distribution, materials and geometrical properties and they are often designed according to the distribution of internal forces, i.e. shear stresses.

The paper provides a general overview of technology, characteristics and design methods according to Eurocode 5.

Keywords: CLT; Concrete; Composite structures; Design methods; Eurocode 5.

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1. INTRODUCTION

Timber as a material, in addition to stone and different types of bricks and ceramic elements, is one of the oldest building materials, and the first structural forms made of timber elements represent the oldest building structures. Historically speaking, timber as a building material had a primary function until the industrial revolution and the use of steel and concrete and the invention of other materials. The beginning of the 20th century brought a new achievement of industrial-technological revolution and progress in all spheres of human activity, including in the construction material industry, i.e. construction. The very rapid expansion of, small cities and towns is required faster and better construction of housing and infrastructure facilities. The building materials industry at the end of the 20th and the beginning of the 21st century significant changes, which greatly contributed to the fact that almost all types of building materials in various spheres of application received new and modified forms and improved properties. The use of natural materials in all areas of modern human activity and modern creativity is considered one of the most important conditions and tasks of today. Environmental awareness, which has been current in recent years in all spheres, even in construction, places timber constructions in one of the leading places, considering the extremely low negative impact on the environment. In addition to the environmental aspect, which is imperative, the economic factor is increasingly considered, i.e. the optimization of the cost price of materials and construction in general. Modern timber constructions are developed in parallel with the development of the chemical industry of glues, paints, varnishes and all other supplements that enable to timber, protection and durability. In addition to solid timber and glued laminated timber, which has always been irreplaceable in the construction of timber structures of different buildings, in the last 20 years, it has been increasingly used, innovative timber-based material called cross-laminated timber (CLT).

The construction of buildings made of CLT is significantly faster compared to the corresponding building made of reinforced concrete, masonry, or steel [4]. When talking about the rational and efficient use of building materials, it is necessary to mention composite structures and materials. By combining different types of materials, a completely new composite material is obtained that retains the good characteristics of the basic materials that form it. The coupling of cross-laminated timber (CLT) and concrete is an innovative way of application of two completely different materials, where the good mechanical characteristics of both are used. The composite floor structures made of CLT and concrete can be designed very successfully, and the main goal of such coupling is to use the good characteristics of concrete in terms of compressive strength and relatively low density of timber.

1.1. Technology, production and geometrical properties of CLT

Cross laminated timber (CLT) is a sophisticated modern product that greatly improved the physical properties of traditional timber as building material. CLT is made of controlled dried timber elements– laminates of uniform width, free of defects (knots, resin etc.). By removing all of the defects and cross-gluing the laminates it is possible to produce the material that has more uniform mechanical properties than the traditional timber. The layers of soft timber are positioned in such manner that the timber grains of adjacent layers are mutually perpendicular. As with plywood, perpendicularly positioned elements create stability; however, greater layer thickness creates panels that are strong enough to be used as a primary structural element without the need for brick or concrete as reinforcement. A CLT cross section contains a minimum of three cross-glued laminates, but most often five or seven. Alternate layers are mutually perpendicular; however, it is possible to double certain layers so that greater strength can be achieved in a desired direction. Laminate height within a CLT varies from 10 to 40 mm while width varies between 60mm and 240mm. Outside laminates within a CLT wall are positioned vertically, parallel with the gravitational forces so that vertical potential of the panel can be maximized, while in CLT panels for floor and roof applications are placed parallel with the direction of dominant forces. To meet aesthetic, fireproof, and insulation requirements, the exposed surfaces of the panels can be covered with gypsum or similar appropriate finish. In Europe, CLT is most often manufactured from conifers grade C24, and moisture content 12±2%, [4]. Panel dimensions are dictated by manufacturer technology and mode of transportation. CLT panels are delivered to a construction site where the wall openings have already been formed according to design. Floor and roof construction are manufactured by arranging the basic panels in horizontal or angular pattern. Typical dimensions of basic floor or roof panel are depicted in Figure 5. Some of the biggest European CLT panels manufacturers are: KLH

(Austria, UK, Sweden), Binderholz (Austria), Martinsons (Sweden), Moelven (Norway), Stora Enso (Austria) and HMS (Germany). All of the above listed manufacturers use the same manufacturing process, while the main differences are panels' dimensions, and the choice of glue. Basic physical and mechanical properties of CLT panels with planks made out of conifers grade C24 (min. 90%) and C16 (max. 10%) are listed in Table 1.

Fig. 1. Cross laminated timber (CLT). Production

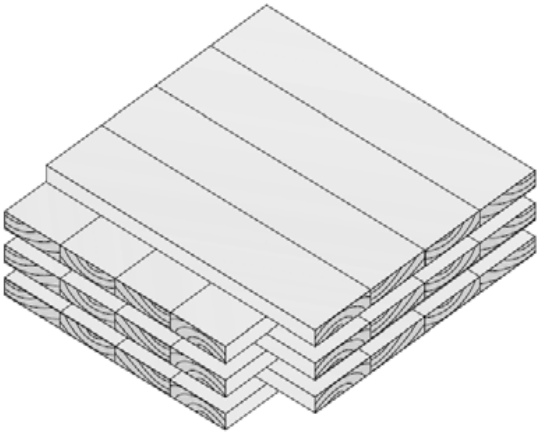

Fig. 2. Cross laminated timber (CLT).

Table 1. Basic physical and mechanical properties of CLT panels according to EN 338 [5]

Characteristic strength C24/T14 [N/mm²]		
Bending	$f_{m,k}$	24 N/mm^2
Tension parallel to the grain	$f_{t,0,k}$	14,5 N/mm^2
Tension perpendicular to the grain	$f_{t,90,k}$	0,4 N/mm^2
Compression parallel to the grain	$f_{c,0,k}$	21 N/mm^2
Compression perpendicular to the grain	$f_{c,90,k}$	2,5 N/mm^2
Characteristic stiffness [N/mm²]		
Mean value of modulus of elasticity, E parallel to the grain	$E_{0,mean}$	11 000 N/mm^2
Mean value of modulus of elasticity, E perpendicular to the grain	$E_{90,mean}$	370 N/mm^2
Density	ρ_k	350 kg/m^3

2. THE STRUCTURAL FORMS OF COMPOSITE CLT-C ELEMENTS

To ensure cooperation of two or more different materials and the formation of a certain composite structural load bearing element, it is necessary to design appropriate connecting system. Connecting systems, which can be of different types, numbers and shapes, are dimensioned and designed to accept and transmit shear forces in the contact planes of the base materials. In practice, timber beam and CLT plate elements can be connected with concrete, efficiently, by adequate connecting system, where, most often a timber element is located in the lower tensioned zone, while a reinforced concrete is located in pressed zone of composite cross section. The connecting systems that join the basic materials can be

adhesive and mechanical, in general, and different shapes and from different materials. For connecting timber and concrete, mechanical connecting systems are most often used, screws, dowels, nails, bolts, steel plates… Fig.3.

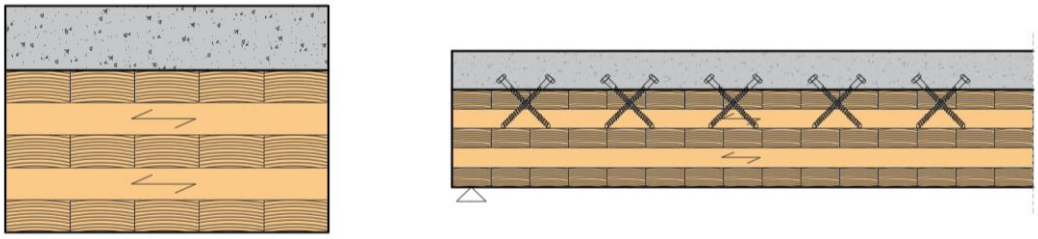

Fig. 3. Composite CLT-C cross section and connecting systems [2]

Coupling timber and concrete using notches of certain shapes and dimensions made in timber in combination with fasteners is a modern innovative system and it is very often applied during the construction of modern buildings. This system increases the contact surface between timber and concrete, and by properly shaping the notch, the concrete can be activated to a certain extent in the transmission of shear force Fig. 4. Based on the efficiency of the connecting systems, the degree of coupling between timber and concrete can be assessed and defined: CLT-C composite structures with rigid action, semirigid or elastic action and composite elements without coupling action [2].

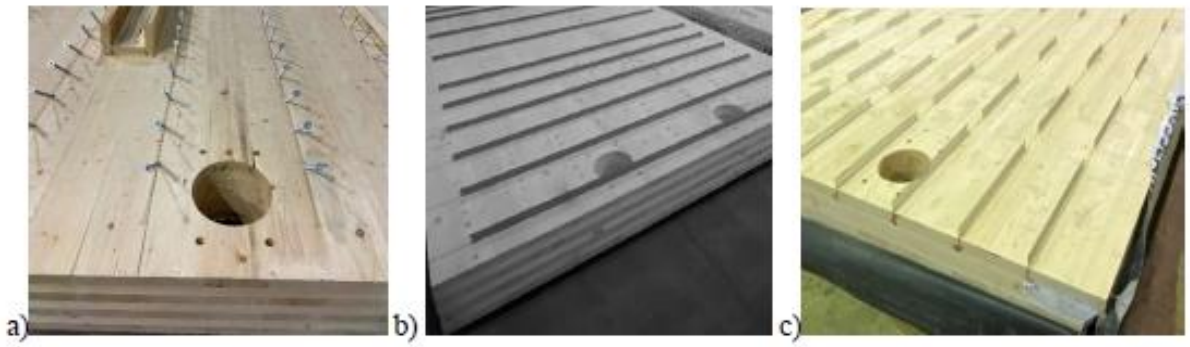

Fig. 4. Connecting systems a) screws, b) kerf plate, c) HBV mesh [2]

3. DESIGN OF CROSS LAMINATED TIMBER-CONCRETE COMPOSITE STRUCTURES (CLT-C-CS). EQUIVALENT GAMMA METHOD

The design of composite structures, in general, especially for complex load combinations, static systems and boundary conditions, can be a very complex procedure [2]. Solving higher order differential equations can be a challenge even for modern computers and software packages that specialize in this and similar types of analysis. In practical calculations, with adopted assumptions and idealizations, it is possible to apply methods and procedures that have proven to be effective and sufficiently precise [1].

The effective bending stiffness of a (CLT-C-CS) floor is analytically evaluated by separating the concrete from the CLT and calculating an effective bending stiffness for each part separately. The effective bending stiffness of each part is then recombined into an equivalent bending stiffness using the Gamma method for the two layers, flexibly connected by the shear connectors.

The CLT section is regarded as a single longitudinal layer in the recombining step, but since the Young's modulus of the transverse layers is equated to zero, the area of the transverse layers is neglected in the calculations. The shear connectors are regarded as the transverse layer of a fictive 3-layer CLT section, where the bottom longitudinal layer is the actual 5-layer CLT and the top layer consists of the actual concrete layer. Fig. 5 illustrates the calculation procedure described in the present paragraph.

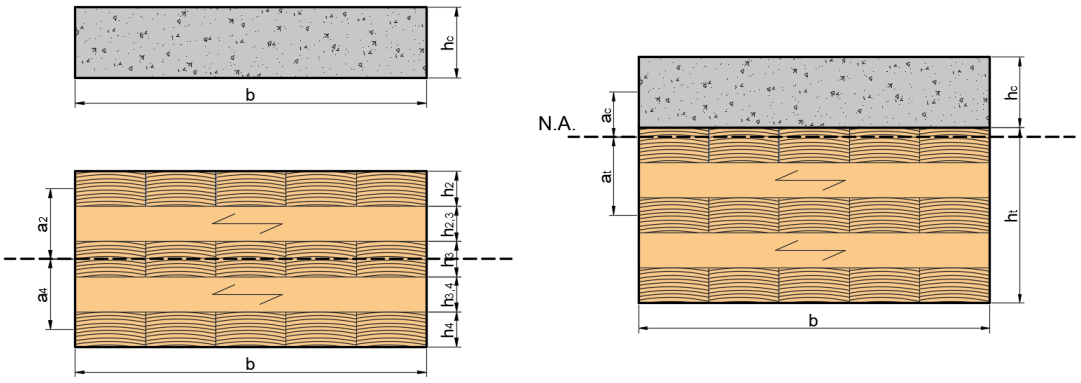

Fig. 5. Explanation of quantities used in the equivalent gamma method.

The bending stiffness of the concrete layer, $(EI)_c$, is calculated as:

$$E_c I_c = E_c / (b_c h_c^3 / 12), \tag{1}$$

where are:

E_c Young's modulus of concrete,
b width of the concrete layer,
h_c height of the concrete layer.

The bending stiffness of the CLT section, (EI)t, is calculated using the Gamma method provided in Annex B of Eurocode 5. The CLT-layers oriented longitudinally in the load bearing direction are assumed to carry load and the transverse layers are neglected since their Young's modulus is approximately $E_t/30$ and therefore equated to zero. The Gamma method is, as previously mentioned, based on a reduction factor, the so called γ-factor, emphasizing the degree of composite action between load bearing layers. The γ-factor ranges from 0 to 1. A γ-factor of 0 corresponds to no composite action between load bearing layers and present layers carry load completely independent of one another. A γ-factor of 1 corresponds to full composite action with no slip between the adjacent longitudinal layers and the present layers cooperate in carrying the load.

$$\left(EI\right)_t = \sum_{i=1}^{n}\left(E_i I_i + \gamma_i E_i A_i a_i^2\right), \tag{2}$$

where are:

E_i Young's modulus of the i-layer,
I_i moment of inertia of the i-layer, calculated as $I_i = b_i h_i^3 / 12$,
γ_i factor reducing the Steiner addition to the moment of inertia of the i-layer,
A_i cross-sectional area of the i-layer, calculated as $A_i = b_i h_i$,
a_i distance between the geometrical center of the i-layer and the neutral axis.

The reduction factor, γ_i emphasises the composite action between two load bearing layers but each layer is given an individual factor. The magnitude of the factor set to 1 for the layer containing the CLT neutral axis since there is no adjacent transverse layer on the side towards the cross-sectional neutral axis. This layer is considered as the base layer. The factors for the remaining timber layers are calculated as:

$$\gamma_i = 1/\left[1+(\pi^2 E_i h_i \bar{h} / G_R l^2)\right], \tag{3}$$

where are:

E_i Young's modulus of the i-layer,

h_i height of the i-layer,
$\bar{h}$ height of the adjacent transverse layer on the side of the i-layer towards the cross-sectional neutral axis,
G_R rolling shear modulus of the present adjacent transverse layer,
l span length of the composite floor.

To determine the distance between the center of the layer of interest and the cross-sectional neutral axis, it is necessary to know the location of the neutral axis of the CLT section. For a symmetric CLT section consisting of identical timber boards, the neutral axis is located at the center of the cross section. The distance, a, for each longitudinal layer can therefore be determined with simple geometry. With a more complex CLT structure the neutral axis can be determined in the same manner as for the TCC explained in Equation 6.

The effective bending stiffness of the TCC section, $(EI)_{eff}$, is calculated using the Gamma method provided in Annex B in Eurocode 5. However, only with consideration of two longitudinal layers, the concrete layer and the entire CLT section, flexibly connected by the shear connectors, seen as the transverse layer of a fictive 3-layer CLT. The concrete layer is seen as the top longitudinal layer and the entire 5-layer CLT section is regarded as the bottom longitudinal layer of the fictive 3-layer CLT. The bearing capacity of the transverse non load bearing layers is still neglected since their Young's modulus are equated to zero. The area of the transverse layers is therefore not included in the area of the CLT section, which instead is only the total area of the longitudinal load bearing layers. Consequently, the effective bending stiffness of the TCC section is calculated as:

$$\left(EI\right)_{eff} = \left(EI\right)_c + \gamma_c E_c A_c a_c^2 + \left(EI\right)_t + \gamma_t E_t A_t a_t^2 \quad (4)$$

$(EI)_c/(EI)_t$ effective bending stiffness of the concrete/timber layer,
γ_c/γ_t factor reducing the Steiner addition to the moment of inertia of the concrete/timber layer
E_c/E_t Young's modulus of concrete/timber
A_c cross-sectional area of the concrete layer, calculated as $A_c = bh_c$,
A_t cross-sectional area of the load bearing layers in the CLT cross section, calculated as $A_t = b\,(h_2 + h_3 + h_4)$,
a_c/a_t distance between the center of the concrete/timber layer and cross-sectional neutral axis.

The CLT section is considered to be the base layer since the there is no adjacent transverse layer on the side towards the cross-sectional neutral axis. The γ-factor for the timber layer is therefore set to $\gamma_t=1$. The γ-factor for the concrete layer corresponds to the characteristics of the shear connectors and is calculated as:

$$\gamma_c = \left[1 + \pi^2 E_c A_c s_{eff} / \left(Kl^2\right)\right]^{-1} \quad (5)$$

E_c Young's modulus of concrete,
A_c cross-sectional area of the concrete layer, calculated as $A_c = bh_c$,
s_{eff} effective spacing between shear connectors,
K stiffness of the shear connector,
l span length of the composite floor.

The position of the neutral axis of the CLT-C floor is required to be known in order to determine the distance between the center of the each longitudinal layer and the cross-sectional neutral axis of the CLT-C floor. As mentioned in the beginning of the present chapter, Equivalent and Extended gamma method both require that the CLT-C neutral axis is located in the CLT section, which is beneficial for the effective bending stiffness as well. With a reference point at the bottom of the cross section, the neutral axis, ***na***, is calculated as:

$$na = \frac{\gamma_c E_c A_c \left(h_t + h_c/2\right) + \gamma_t E_t A_t \left(h_t/2\right)}{\gamma_c E_c A_c + \gamma_t E_t A_t}. \quad (6)$$

With known location of the neutral axis, the distance between the center of the present layer and cross-sectional neutral axis can be calculated regarding the concrete layer and regarding the timber layer according to fallowing equations:

$$a_c = h_t + h_c / 2 - na \qquad a_t = na - h_t / 2 \tag{7-8}$$

4. ULTIMATE LIMIT STATE

The normal stress distribution in the concrete layer and in the longitudinal CLT layers are determined individually by calculating the normal stress at the top and bottom of each layer. The total normal stress is affected by the normal stress, σ_i, taking the coupling effect into account, and the normal stress, $\sigma_{m,i}$, taking the distribution over the height of the layer into account. The different normal stresses and the stress distribution over the height of the CLT-C floor is illustrated in Fig. 6.

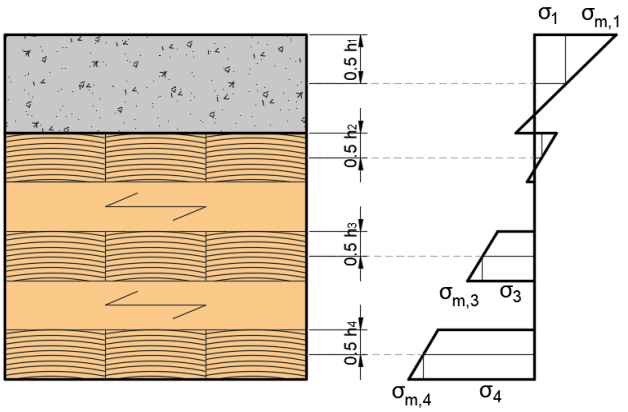

Fig. 6: Stress distribution over the CLT-C cross section height.

The stresses are calculated according to Eurocode 5, Annex B.3:

$$\sigma_i = \gamma_i E_i a_i M / (EI)_{eff} \tag{9}$$

$$\sigma_{m,i} = 0{,}5 E_i h_i M / (EI)_{eff} \tag{10}$$

γ_i gamma factor of the i-layer representing the coupling effect,

E_i Young's modulus of the i-layer,

a_i distance between the geometrical center of the i-layer and the cross-sectional neutral axis,

hi height of the i-layer,

$(EI)_{eff}$ effective bending stiffness of the CLT-C floor,

M_d max. design bending moment

A shear stress verification is only relevant for the CLT section. The shear stress is determined due to longitudinal shear, τ_i, in the longitudinal layers and due to rolling shear, $\tau_{R;i}$, in the transverse layers. The largest shear stress in the CLT section occurs where the normal stress is zero, i.e. at the location of the cross-sectional neutral axis. As such, the layers of interestare the longitudinal and transverse layer at or next to the neutral axis.

$$\tau_i = E_i S_i V_d / \left(b (EI)_{eff}\right) \qquad \tau_{R,i} = E_i S_{R,i} V_d / \left(b (EI)_{eff}\right) \tag{11}$$

The force acting on a shear connector due to the shear force, depends on the properties of the concrete layer. The force, F_i is calculated according to Eurocode 5 Annex B.5.

$$F_i = \gamma_i E_i A_i a_i s_i V / (EI)_{eff} \tag{12}$$

5. CONCLUSION

Composite structures made of cross-laminated timber-CLT and concrete (CLT-C) are modern structural elements that have found great use in construction, due to their exceptional physical and mechanical properties and simplicity during the building erection. The paper presents the some part of design method given in Eurocode 5, annex B for practical calculations, with adopted assumptions and idealizations for this type of structures. Based on all previous research, it can be concluded that the use of natural and renewable building materials will be increasingly intensive in the future and will not represent a choice, but an obligation, with the aim of reducing pollution and protecting the environment. Composite CLT-C structures meet the requirements of ecological aspects, and their impact on the environment is many times smaller compared to the other materials.

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